Importance of oceanic decadal trends and westerly wind bursts for forecasting El Niño

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Abstract. In the western Pacific, Westerly Wind Bursts (WWB) usually show up in the boreal fall-winter season, depending on the activity of the Madden and Jullian oscillation. It is demonstrated with a coupled ocean-atmosphere model that WWB have an impact on the coupled system in El Niño forecasting that depends on the ocean preconditioning. Sea level data reveal decadal changes of the Ocean Heat Content of the entire tropical Pacific (the OHC), with a minimum in the mid-1980s relative to highs before 1982 and after 1996. Adding the WWB in the forecast system does not degrade the successful predictions when the OHC is low whereas WWB are necessary in winter 1981-82 and 1996-97 to successfully predict the forthcoming warm events. Thus, when the OHC is high in addition to the other traditional conditions being favorable for a warm growth, WWB contribute to having a strong El Niño event the following year.

1. Background

The last twenty years have seen two El Niño warm events which were among the strongest on record. As illustrated for the last big event (*McPhaden*, 1999), observation systems now allow us to monitor the seasonal to interannual changes of our climate. Although considerable progress has been done in simulating the oceanic and atmospheric interannual variability with numerical models, predicting a warm event one year in advance is still a big challenge. All the coupled ocean-atmosphere systems available for forecasting failed to predict the large 1997-98 El Niño (for a review, see *Barnston et al*, 1999). *Wyrtki* (1985) highlighted that monitoring the slow water displacements in the western Pacific can provide some insight on the likelihood of a coming warm event. At the same time, *Barnett* (1984) suggested that the rapid changes of surface winds over the Indonesian region, known as Westerly Wind Bursts (WWB), play a role in ENSO (El Niño Southern Oscillation). With the end of the TOGA program, it became clear that the oceans beyond the equatorial regions should no longer be neglected, because their low-frequency variability influences ENSO (*Gu and Philander*, 1997). Here, we examine the decadal oceanic variations and the high-frequency atmospheric ones by using observations over the period 1980-1998 and we illustrate their combined role on ENSO forecasts with a coupled ocean-atmosphere model.

2. Off-equatorial ocean

Sea level variations relative to their climatology over January 1980- December 1996 have been estimated using a combination of hydrographic measurements and TOPEX-Poseidon satellite data (see *Perigaud et al*, 1999 for details). Positive (negative) anomalies correspond to heat content in excess (deficit) compared to the normal conditions. These data averaged over the Pacific ocean between 5º and 15º North or South reveal signals that are quite different in the two hemispheres (Fig. 1a). Indeed, the time series tend to have anti symmetric fluctuations over most of the 19 years. The North is recharged after the 1982/83, 1986/87 and 1991/92 El Niño events (the vertical bars in Fig. 1a indicate the dates when the El Niño events reach their warm peak phase) in contrast to the South. In addition note the decadal trends undergone by both signals. Data highlight the uniqueness of each event. In particular, the situation prior to 1982 is quite different from the one prior to 1996, with opposite signs in the North.

The coupled model presented in *Cassou and Perigaud* (1999) simulates sea level anomalies positive on average in the North and negative on average in the South after each warm peak (Fig. 1b). These oceanic variations are in quasi-Sverdrup balance with the model wind, i.e. westerlies between the equator and 10ºS, and northerlies in the Central-Eastern Pacific between 5ºN and 15ºN. These zonal and meridional wind anomalies agree well with the ones observed during and after the warm events of the 1983-1994 period. The model simulates mature warm events and their decays associated with an anticyclonic wind curl in the North and a cyclonic curl in the South. They correspond to sea level charges and discharges that fit reasonably well the observed ones between 1983 and 1994. The model however does not reproduce the observed decadal trends.

After initialization with observations, the coupled model has been used to generate series of two-year long forecasts over the 1980-1998 period (see *Perigaud et al.* , 1999). As illustrated in Fig. 2, the observed Niño3 index for Sea Surface Temperature (SST averaged between 90ºW-150ºW, 5ºS-5ºN) is predicted with some success, including lead-times as long as one year. Detailed validation of the forecasts with data indicates that the model is similarly skilled over all the period 1983-1994. It is skilled for predicting not only the SST, but also the sea level anomalies and the two wind components over the entire tropical Pacific. In addition, this success is robust and holds whether the model is initialized with sea level, wind or SST observations, with a combination of them, or with the data-model nudging applied *in Chen et al* (1995). *Perigaud et al* (1999) highlight the sensitivity of the forecasts to the off-equatorial ocean and wind anomalies. Among other factors, the model skill at one-year lead time is explained by its ability to simulate mechanisms involving the coupling between the off-equatorial oceanic and atmospheric anomalies that resemble the ones observed over this period.

By contrast, the model fails to predict one year in advance the big warm events of 1982-1983 and 1997-1998. To try and improve the predictive skill for these two events, we generated many forecasts after choosing a parameterization to increase the coupling strength, or adding positive feedback mechanisms such as latent heat exchanges. Sea level data were also used to initialize the model and test if these data improve the predictions like in *Chen et al* (1998). By contrast with the latter where the nudging gives very little weight to the sea level data in the off-equatorial ocean, choice is made here like in *Perigaud et al* (1999) to use the data with a uniform weight over the entire tropical Pacific, resulting in initial conditions that are improved mostly poleward of 5º of latitude. Not a single test among so many was successful to improve the forecasts of the two strong events: the model always fails to predict the 1982/83 El Niño event for initial conditions prior to May 1982 and always fails to predict the 1997/98 event prior to March 1997. It is concluded that something fundamental besides the off-equatorial oceanic heat content is missing in the model.

3. Westerly Wind Bursts (WWB)

The largest misfit between the observed and simulated winds is located in the western Pacific. Indeed, this region is subject to a strong wind variability at relatively high-frequencies associated with the occurrence of Westerly Wind Bursts. Evidence of WWB is found in the monthly averaged ship data analysis provided by Florida State University (*Goldenberg and O'Brien*, 1981) as illustrated in Fig. 3a. This figure presents the time series of a WWB index defined as the average of the zonal wind stress anomalies west of the dateline between 12ºS-12ºN. This index varies very irregularly from month to month. WWB are found in boreal fall and winter more often than in spring or summer. It is unusual to find WWBs during winters of El Niño years, but November 1986 is a case when there were strong WWB although the warm event was already well developed (also found *in Picaut and Delcroix*, 1995). For the sake of simplicity, we retain as "WWB", the wind anomalies which have an index larger than 0.025 Pa (represented by the horizontal bar on Fig. 3a). The individual "WWB" cases that are thus selected correspond to a wide variety of patterns with a center of action located either North, South or along the equator. On average (Fig. 3b), the "WWB" cases have a strong eastward component with values reaching 0.04 Pa in the western Pacific between 5ºS and 5ºN.

Because the atmospheric component of the model drastically lacks variability West of the dateline, introducing some parameterization of WWB in the model may improve the simulations. This is achieved by adding to the atmospheric model component, the WWB pattern presented in Fig. 3b multiplied by a factor varying in time which is *a priori* prescribed. One difficulty lies in defining this time factor, the predictability of WWB being highly uncertain. It is tempting to say that WWB are the strongest during the winters preceding strong El Niño events, but Fig. 3a indicates that this is not always a valid relationship (the horizontal bar on this figure also corresponds to the 1ºC SST level, and the vertical bars to the peaks of the El Niños). WWB did not show up in winter 1990-91 nor winter 1985-86. Similarly, it is not easy to find evidence of a strong relationship between the WWB index and the local characteristics in SST or sea level of the western Pacific.

To simplify the problem, WWB are introduced with a time factor equal to 1. continuously applied during the 3 months of November, December and January and only for the years when the observed WWB index is larger than 0.025 Pa, i.e. in 1981-82, 1982-83, 1986-87, 1989-90, 1990-91 and 1996-97. In reality, individual WWB are stronger than in Fig. 3b, but they do not last 3 months in a row. The sole objective here is to investigate whether the coupled model is sensitive to WWB or not. Tests have been done with other combinations of amplitude and duration. They give similar results. The 1981-83 and 1996-98 forecasts delivered by the model in the standard configuration are presented in Fig. 4ab. These figures provide the reference of the model performance without the WWB implementation. Fig. 4cd presents the results when the WWB pattern is applied during the 3 months of winter 1981-82 or 1996-1997 as explained above. The impact of the WWB is very big for these two forecast series. Adding WWB is the one modification of the model which allows to successfully predict the warm growth. This success is quite remarkable given the large number and variety of model modifications that have been tested and that failed.

It is also quite remarkable that by contrast, adding WWB during other years has little impact on the forecasts (not shown). In winter 1982-83 or 1986-87, adding WWB does not degrade the predictions of the warm decays, because the western Pacific which is responsible for the reversal of the warm growth, is already a cold reservoir then. In 1990-91, sea level data also show that the western Pacific was not anomalously warm but slightly cold, which explains why WWB have little impact on the subsequent forecasts. In winter 1989-90, the western Pacific sea level was high, but adding WWB does not make the model switch erroneously to a warm state for a different reason: most of the equatorial-South Pacific was cold (see Fig. 1a) and the SST of the eastern Pacific during several months after was cold enough (see Fig. 3a) to maintain the coupled system in a stable regime. Finally, note that for the same WWB applied to the model, the warm event predicted since winter 1981-82 is weaker than the one since winter 1996-97. These results are further interpreted in terms of relationship with the variations of the observed oceanic heat content of the entire tropical Pacific during the past 19 years since 1980.

4. Role of WWB and Oceanic Heat Content (OHC)

The OHC index is defined as the average of sea level in the tropical Pacific between 15ºS and 15ºN. The North and South signals presented in Fig. 1a added to the equatorial contribution (weighed by their respective surface) then give the OHC. As expected, the OHC variations have most of their energy in the 3 to 7 year band like ENSO, but in addition, it is striking that the OHC exhibits interdecadal trends (Fig. 5). The 1984 to 1994 decade contrasts with the beginning (1980-1982) and the ending (1996-1997) of the period considered here. Both extremities correspond to strong positive anomalies, meaning a significant excess of heat accumulation in time. The low-frequency variations of the OHC are proposed here as a measure of the degree to which the WWB are active on the coupled system. The forecast results described above indicate that when the OHC is low, the WWBs have very little impact on the predictions because either the western Pacific or the eastern Pacific or both are not preconditioned for a warm growth then. The great warm growth in the 1996-98 case happens after an increase of OHC that took place over many years since 1984. This event was stronger than the 1982-83 case, which is well reproduced by the model forecast although the same strength of WWB is applied. Even though the relationship is not linear, results indicate that there is a possible link between the OHC interdecadal trend and the ability of WWB to grow warm events when all the other conditions usually monitored are also favorable.

It is expected that westerly wind bursts induce warm subsurface temperature anomalies from the western Pacific to the eastern Pacific (see Fig. 1a) and that the anomalously warm waters in the eastern Pacific tend to weaken the trade winds in the central Pacific, thus having a positive feedback. But it is the conjunction of all effects, i.e. the impact of WWB with a charged western Pacific on a not too cold eastern Pacific, and the concomitance of the charged OHC and the WWB, that is crucial for the coupled system to shift into a growing mode leading to a big El Niño. It is quite possible that WWB are sensitive to the entire tropical Pacific ocean heat content. Local energetic atmospheric features like WWB do depend on atmospheric-land-ocean large scale processes. The latter vary very slowly. The fact that the activity of the Madden Julian Oscillations is not controlled by the phase of El Niño, showing mainly a chaotic behavior superimposed on a decadal time-scale variability is consistent with the results of *Slingo et al* (1999). When the low-frequency component of the OHC corresponds to many years of heat accumulation, westerly wind bursts can ensure the oceanic discharge. The OHC is proposed here as one index, in addition to the conventional ones (sea level in the western Pacific and SST Niño3), worthwhile monitoring to predict the impact of WWB in triggering big warm events.

5. Discussion

The most important result of this paper is that WWB have an impact on the coupled system in its ability to grow a warm event that depends, among others, on the oceanic heat content of the entire tropical Pacific. This result is demonstrated with a coupled ocean-atmopshere model and is supported by observations.

As any model results, the ones presented above are dependent on the model equations and its parameterizations. Because the coupled ocean-atmosphere model used here is based on simplified physics, it is first and foremost a tool for testing ideas rather than an operational system to be used for predictions. Results of experimenting this tool lead to the following message. The WWB in fall-winter 1981/82 and 1996/97 played a strong role in triggering the warm events, whereas their role was not as important during the other years. These results are robust, because the forecast outputs have been thoroughly validated with data (like in *Perigaud et al*, 1999) and because all the different experiments performed changing reasonably the initial conditions or the model parameters lead to the same conclusions. The forecasts without WWB fail to predict the two big warm events, or if they successfully predict the Niño3 SST index they have flaws somewhere else in their oceanic or atmospheric predicted anomalies. The forecasts with WWB remain successful for other reasonable choices of amplitude or duration of the time factor. The success of the 1981/82 and 1996/97 forecasts with WWB is robust and not based on the sole analysis of the Niño3 SST index.

Observations exhibit strong WWB when the entire tropical Pacific has been accumulating heat over many years. The combination of the model results and the observations suggests that in addition to monitor the oceanic heat content of the western Pacific as a possible precursor of El Niño, it is worth to monitor the OHC over the entire tropical Pacific. The accuracy needed is 1 cm. In the present study, only years 1992 to 1998 are covered with such an accuracy. The interdecadal change of sea level since 1980 is found consistent with the one observed over the Indian Ocean and that of winds over both oceans, supporting the validity of the message brought here, even though the observed sea level is less accurate prior to the satellite mission. In addition, note that the North and South sea level anomalies in 1997-98 are very different from the ones in 1982-83. If the estimates prior to 1991 had the accuracy of TOPEX-Poseidon, it would be worth refining this study to demonstrate how every little detail counts in a coupled system like our climate.

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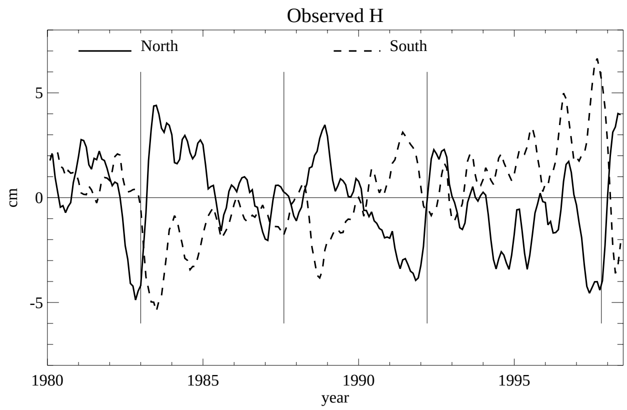
Figure 1. Time series of sea level anomalies averaged over the Pacific (130ºE-80ºW) between 5º and 15º of latitude North (solid line) or South (dashed line). Top panel corresponds to observations, bottom to coupled model simulations.

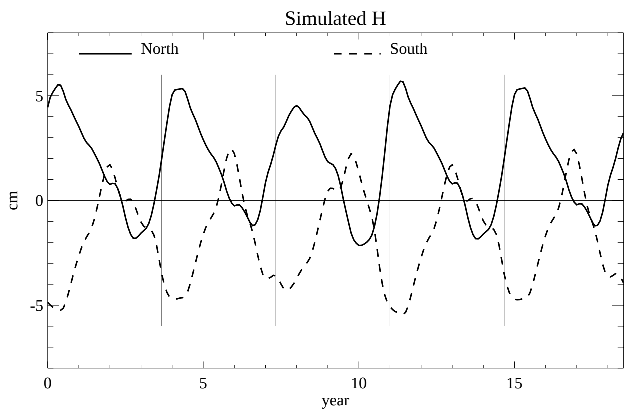
Figure 2. Time series of SST Niño3 indices derived from observations (solid), model initial conditions (dashed) or predictions (dotted) over various two-year long periods.

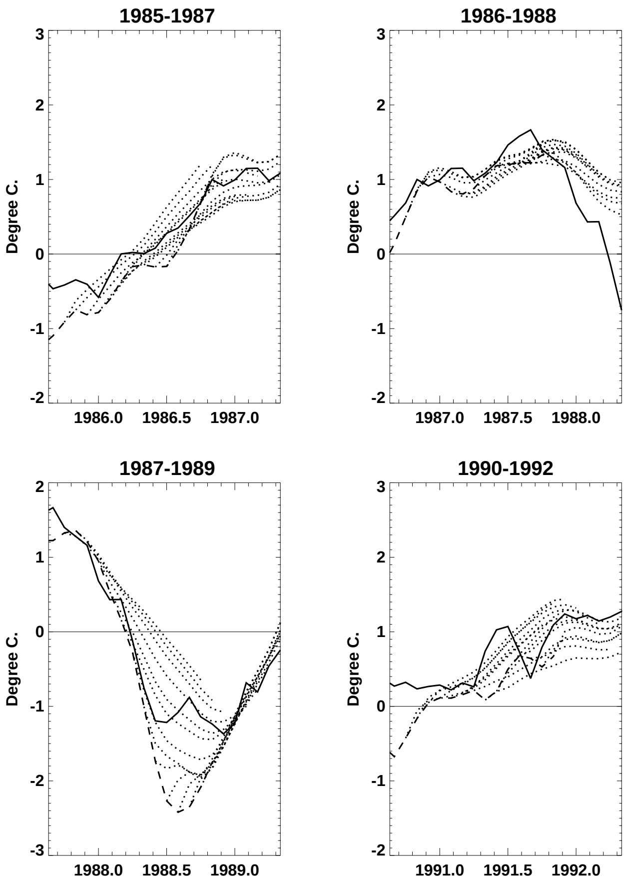
Figure 3. WWB index and spatial pattern. Top panel presents the time series of the WWB index (solid) and the SST Niño3 index (dotted) with scales in Pa and ºC given on the left and right axis respectively. The bottom map with isocontours of 0.01 Pa is the average of the wind anomalies for all the cases of WWB indices > 0.025 Pa.

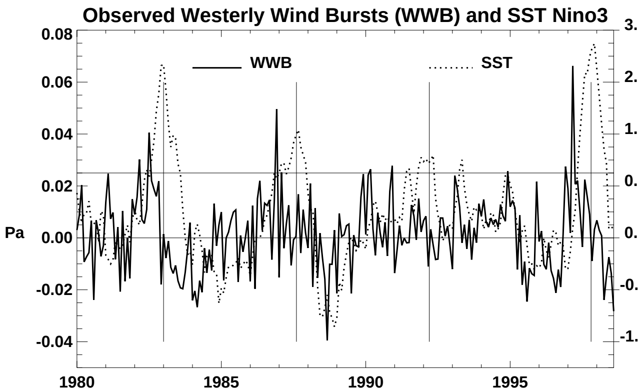
Figure 4. Same as Fig.2 for the 1981-1983 and 1996-1998 cases. The bottom panel correspond to forecasts where the WWB pattern is added as described in the text.

Figure 5. Time series of the observed OHC (solid) and WWB (dotted) indices with scales in cm and in Pa given on the left and right axis respectively.

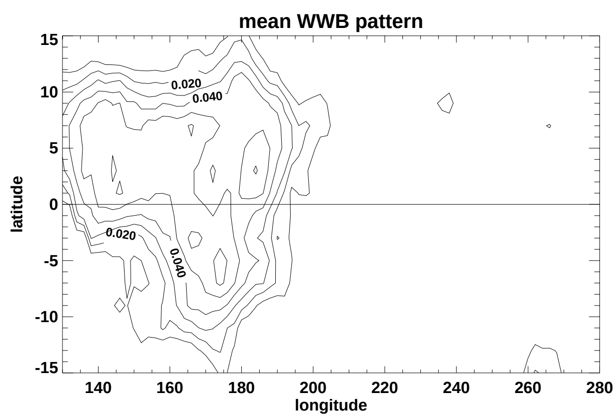

Observed H
North
South
cm
5
0
-5
1980
1985
1990
1995
year


Simulated H
North
South
cm
5
0
-5
0
5
10
15
year

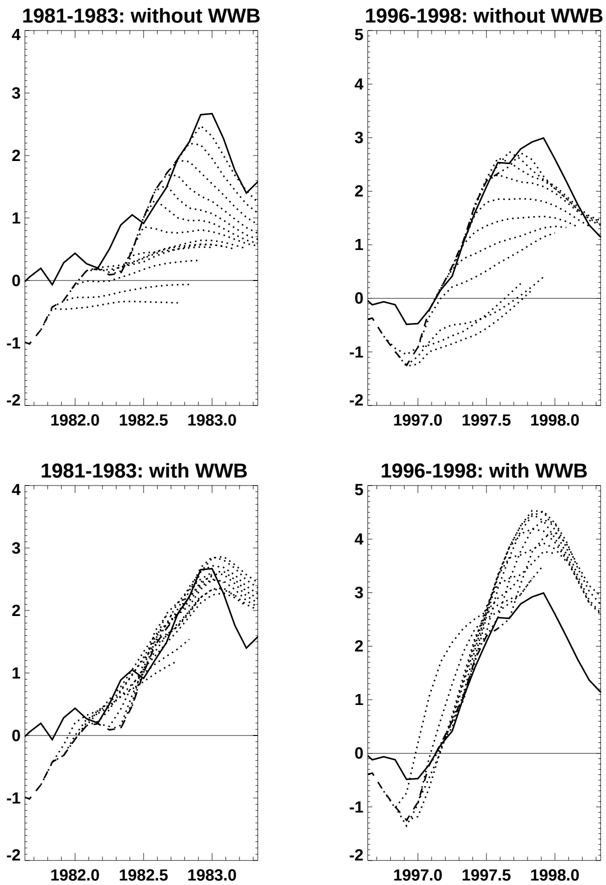

1985-1987
Degree C.
1986.0
1986.5
1987.0
1986-1988
Degree C.
1987.0
1987.5
1988.0
1987-1989
Degree C.
1988.0
1988.5
1989.0
1990-1992
Degree C.
1991.0
1991.5
1992.0

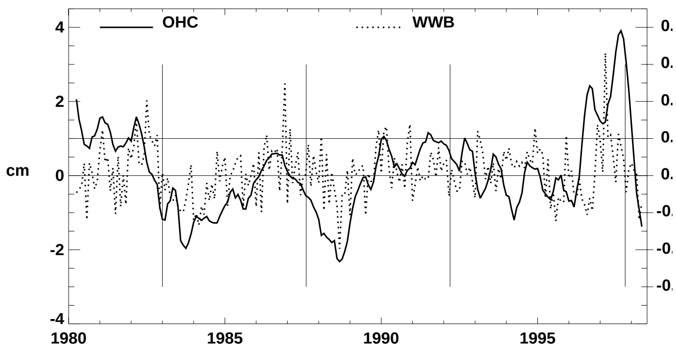


Observed Westerly Wind Bursts (WWB) and SST Nino3
WWB
SST
Pa
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
3.
2.
1.
0.
0.
-0.
-1.
1980
1985
1990
1995



mean WWB pattern
0.020
0.040
0.020
0.040
latitude
15
10
5
0
-5
-10
-15
140
160
180
200
220
240
260
280
longitude


1981-1983: without WWB
1996-1998: without WWB
1981-1983: with WWB
1996-1998: with WWB
4
3
2
1
0
-1
-2
5
1982.0
1982.5
1983.0
1997.0
1997.5
1998.0



OHC
WWB
cm
4
2
0
-2
-4
1980
1985
1990
1995